

The Araucaria Project. The Distance to the Sculptor dwarf spheroidal galaxy from infrared photometry of RR Lyrae stars ¹

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ABSTRACT

We have obtained single-phase near-infrared magnitudes in the J and K bands for a sample of 78 RR Lyrae stars in the Sculptor dSph galaxy. Applying different theoretical and empirical calibrations of the period-luminosity-metallicity relation for RR Lyrae stars in the infrared, we find consistent results and obtain a true, reddening-corrected distance modulus of 19.67 ± 0.02 (statistical) ± 0.12 (systematic) mag for Sculptor from our data. This distance value is consistent with the value of 19.68 ± 0.08 mag which we obtain from earlier V-band data of RR Lyrae stars in Sculptor, and the V magnitude-metallicity calibration of Sandage (1993). It is also in a very good agreement with the results obtained by Rizzi (2002) based on tip of the red giant branch (TRGB, 19.64 ± 0.08 mag) and horizontal branch (HB, 19.66 ± 0.15 mag).

Subject headings: distance scale - galaxies: distances and redshifts - galaxies: individual(Sculptor) - stars: RR Lyrae - infrared photometry

1. Introduction

The main goal of the Araucaria project is to improve the calibration of the cosmic distance scale from accurate observations of the various primary stellar distance indicators in nearby galaxies (e.g. Gieren et al. 2005b). In particular, we are significantly improving the distance measurements to the Araucaria target galaxies using IR photometry, which minimizes both the influence of interstellar extinction, and of metallicity and/or age on the brightness of stellar distance indicators. Indeed, in our previous papers we have demonstrated that the red clump stars (Pietrzynski and Gieren 2002; Pietrzynski, Gieren and Udalski 2003), and Cepheid variable stars (e.g. Pietrzynski et al. 2006; Gieren et al. 2005a, 2006, 2008; Soszynski et al. 2006) are outstanding distance indicators in the near-infrared domain.

Thanks to several recent and important theoretical and empirical studies of RR Lyrae stars we have now good reasons to believe that RR Lyrae stars are also capable of providing much improved distances from their magnitudes in the near-infrared regime, as compared to the traditional optical studies. Longmore et al. (1986) were the first to show that RR Lyrae stars follow a period-luminosity (PL) relation in the K band. Then important contributions were added by Carney et al. (1992), Nemec et al. (1994), Jones et al. (1993) Frolov and Samus (1998) and Bono et al. (2001). Dall’Ora et al. (2004) later demonstrated that such a relation could be very tight for RR Lyrae stars in a globular cluster, with its very low metallicity spread. Detailed theoretical studies of the RR Lyrae period-mean magnitude-metallicity relations in different near-infrared passbands were done by Bono et al. (2003), and Catelan et al. (2004). Sollima et al. (2006) analyzed near-infrared K-band data of RR Lyrae stars for some 15 Galactic globular clusters and provided the first extensive empirical calibration of the period-luminosity-metallicity (PLZ) relation in the K band. Most recently, the zero point of this relation was improved based on accurate near-infrared observations of the RR Lyrae star (Sollima et al. 2008). These existing theoretical and empirical results have demonstrated that a near-infrared PLZ relation for RR Lyrae stars appears to be a very accurate means for distance determination to galaxies containing an abundant old stellar population. We are therefore including this tool in our project and expect that we will be able to improve on its current calibration by conducting near-infrared observations of large numbers of RR Lyrae variables in a number of nearby galaxies, and comparing the resulting RR Lyrae distances to those emerging from other methods, like the TRGB technique.

With its rich population of both RRab and RRC stars which span a wide range of metallicities (Clementini et al. 2005), the Sculptor dwarf spheroidal galaxy is an ideal laboratory for studying the infrared PLZ relations defined by these variables. Therefore we included this galaxy in the target list of the Araucaria project. In this paper, we present first results from deep single-phase near-infrared imaging of 78 RR Lyrae stars in Sculptor. We will show that these data allow a distance determination for Sculptor with very small intrinsic error.

2. Observations, Data Reduction and Calibration

The near infrared data presented in this paper were collected as a part of the Araucaria Project, with the ESO NTT telescope on La Silla equipped with the SOFI infrared camera (Moorwood, A., Cuby, J.G., Lindman, C., 1998) . The Large Field setup, with a field of view of 4.9 x 4.9 arcmin, and a scale of 0.288 arcsec/pixel was used. During one photometric

night we observed two fields in Sculptor, which contain a large number of RR Lyrae stars. Their locations are shown in Fig. 1. We secured single deep J and Ks observations for each field under excellent ($0.6''$) seeing conditions. In order to account for rapid sky level variations in the infrared domain, our observations were performed with a dithering technique. The resulting total integration times were 44 and 21 minutes for Ks and J band images, respectively.

All reductions and calibrations were performed with a pipeline developed and used in the course of the Araucaria Project. Briefly, the sky subtraction was applied in two-step process implying masking of stars with the XDIMSUM IRAF package (see Pietrzyński and Gieren (2002) for more details). Then the single images were flat-fielded and stacked into the final, deep images. PSF photometry and aperture corrections were derived using DAOPHOT and ALLSTAR programs, in an identical manner as described in Pietrzyński, Gieren, and Udalski (2002).

In order to calibrate our photometry to the standard system 9 standard stars from the UKIRT list (Hawarden et al. 2001) were observed under photometric conditions at different airmasses together with our target fields. The chosen standards have colors which bracket the colors of the RR Lyrae stars in Sculptor. Given the large number of standard stars the accuracy of the zero point of our photometry was estimated to be about 0.02 mag.

In order to make an external check of our photometry the magnitudes of the bright stars in our fields were transformed onto the 2MASS photometric system and then compared with the 2MASS photometry. We found the following differences (in the sense 2MASS photometry minus our results): -0.01 ± 0.11 mag (K), -0.03 ± 0.13 mag (J).

The J and K band magnitudes of the observed RR Lyrae stars, together with the corresponding errors as returned by DAOPHOT, and the time of the beginning of each exposure are given in Table 1.

3. Near-Infrared Period-Luminosity Relations

Since the IR light curves of RR Lyrae stars are nearly sinusoidal and have relatively small amplitudes (e.g. Del Principe et al. 2006), single-phase measurements of J and K magnitudes of RR Lyrae stars give approximations of reasonable accuracy to their mean magnitudes in these bands. The PL relations in J and K we obtain from our random single-phase data are presented in Fig. 2. Two sequences are clearly visible, corresponding to the first overtone (RRc) and fundamental mode (RRab) pulsators, respectively. The relatively large scatter observed in this Figure is caused by the three following factors:

Firstly, a single phase IR measurement is expected to approximate the mean magnitude of a RR Lyrae variable to about 0.15 mag only. Secondly, a rather large spread of metallicities is observed for the RR Lyrae stars of this galaxy (Clementini et al. 2005, Kaluzny et al. 1995). Clementini et al (2005) determined a mean metallicity (on the Zinn and West scale) of RR Lyrae stars of -1.83 ± 0.26 dex. Assuming a metallicity dependence in the K and J bands of 0.175 and 0.190 mag/dex, respectively (Catelan et al. 2004), we expect an additional scatter in the IR magnitudes of Fig. 2 of about 0.05 mag (one σ) due to the metallicity inhomogeneity of our sample of RR Lyrae stars in Sculptor. Finally, the accuracy of our individual magnitudes is between 0.04 and 0.07 mag for stars having K band magnitudes in the range from 18.6 to 19.5. Clearly, the largest source for the scatter in Fig. 2 is the replacement of mean magnitudes derived from complete light curves by the single-phase observations. Unfortunately due to a very large gap between the optical survey by Kaluzny et al. (1995) and our IR observations it is not possible to use the template light curves provided by Jones et al. (1996) to calculate more accurate mean magnitudes.

The slopes of the PL relations followed by the RRab and RRC stars, and by the whole, combined RRab+RRC sample of RR Lyrae stars as obtained from free least-square fits to a line in both J and K band filters are given in Table 2. In order to merge the first overtone and fundamental pulsators, a value of 0.127 was added to the logarithm of the periods of the RRC stars, following Dall’Ora et al. (2004). Unfortunately, the relatively large errors associated with these slope determinations do not allow us to conduct a detailed discussion on these results. We can only conclude that within the limited accuracy we can achieve in this study we cannot detect any significant difference between the slopes of the K- and J-band PL relations obtained for the RRC and RRab stars, respectively. The slopes agree furthermore very well with both, the existing theoretical (Bono et al. 2003, Catelan et al. 2004) and empirical (Sollima et al. 2008) slope results obtained for field RR Lyrae stars.

4. The Distance Determination

In order to derive the apparent distance moduli to the Sculptor galaxy from our data, we used the following calibrations of the near-infrared PL relations of mixed population RR Lyrae stars:

$$M_K = -1.07 - 2.38 \log P + 0.08 [\text{Fe}/\text{H}] ; \text{ Sollima et al (2008) (1)}$$

$$M_K = -0.77 - 2.101 \log P + 0.231 [\text{Fe}/\text{H}] ; \text{ Bono et al. (2003) (2)}$$

$$M_K = -0.597 - 2.353 \log P + 0.175 \log Z ; \text{ Catelan et al. (2004) (3)}$$

$$M_J = -0.141 - 1.773 \log P + 0.190 \log Z ; \text{ Catelan et al. (2004) (4)}$$

We recall that the calibration of Sollima et al. (2008) was constructed for the 2MASS photometric system, while the calibrations of Bono et al. and Catelan et al. are valid for the Bessel and Brett and Glass systems. Therefore, we transformed our own data, calibrated onto the UKIRT system (Hawarden et al. 2001), to the Bessel and Brett and Glass systems using the transformations given by Carpenter (2001), before calculating distances using the calibrations of Bono et al. and Catelan et al., respectively. Since there is virtually no difference between the K-band filters of 2MASS and UKIRT (Carpenter 2001), we did not apply any transformations to our data for the Sollima et al. calibrations.

Assuming the mean metallicity of our RR Lyrae sample to be -1.83 ± 0.26 dex (Clementini et al. 2005), we calculated the K- and J- band apparent distance moduli as tabulated in Table 3. The corresponding fits to a straight line are presented in Figure 3. The calculations were made for the RRab star sample alone, and for the combined sample of RRab and RRC stars, after adding 0.127 in logarithm of period to the RRC stars. The results obtained for both samples are in an excellent agreement (within 0.5σ), so hereinafter we decided to adopt the slightly more accurate results from the whole sample of RR Lyrae stars observed in this galaxy (e.g. RRab and RRC) for further discussion.

To correct the obtained apparent distance moduli for interstellar reddening, we adopted a foreground reddening of $E(B-V) = 0.018$ mag which is calculated toward the Sculptor galaxy from the Galactic extinction maps of Schlegel et al. (1998). Assuming the reddening law from this same paper we obtain the following values for the selective extinctions in the different bands: $A_K=0.007$ mag, $A_J=0.017$ mag, $A_V=0.059$ mag. The resulting true distance moduli for Sculptor are summarized in Table 4. We also include the true distance modulus to the Sculptor galaxy from the optical V band data of Kaluzny et al. (1995) in this Table.

5. Discussion

The results in Table 4 demonstrate that the true distance moduli obtained from the theoretical calibrations of the RR Lyrae PLZ relation in the J and K bands of Catelan et al.

(2004) are practically identical. They also agree very well with the results obtained from the empirical calibration of Sandage (1993) for the V band, and the V-band data of Kaluzny et al. 1995. This hints at a very small internal reddening produced inside the Sculptor galaxy. The distance moduli obtained from the independent theoretical calibration of Catelan et al. (2004) and Bono et al.(2003) and empirical calibration of Sollima et al. (2008) in the K band, are different by some 0.05 mag. Such a difference is not significant taking into account all uncertainties involved in those calibrations.

There are several sources of systematic error in our procedure of distance determinations. Taking into account the uncertainties of the coefficients of the adopted calibrations, on the one hand; assuming an error of the adopted mean metallicity of our RR Lyrae sample of 0.26 dex as given by Clementini et al. (2005); assuming an accuracy of the photometric zero points of 0.02 mag; and finally, taking into account an uncertainty of 0.01 mag associated to the absorption correction, we estimate the systematic errors on each of the distance determinations as listed in Table 4. They are significantly larger than the corresponding statistical errors and are dominated by the errors associated with the uncertainty of the assumed (constant) metallicity of the individual RR Lyrae stars in our sample.

We adopt from our study 19.67 ± 0.02 (statistical) ± 0.12 (systematic) mag (e.g. the mean value) as the true distance modulus of the Sculptor dSph galaxy. Unfortunately, there is very little information about the distance to Sculptor galaxy in the literature. Our adopted distance agrees very well with the results obtained by Rizzi (2002) from the optical photometry of the TRGB (19.64 ± 0.08 mag) and HB (19.66 ± 0.15 mag).

Our results also indicate that the systematic errors of the different empirical and theoretical calibrations in the literature were probably estimated quite conservatively and may in fact be smaller. We will be able to check on this more closely once we can compare the present results from IR photometry of RR Lyrae variables with distance results from other techniques.

29 RR Lyrae stars from our sample are in common with the list of RR Lyrae stars with metallicity determinations reported by Clementini et al. (2005). This provides an opportunity to calculate distances to individual stars based on equations (1-4) and then compare the results with the values obtained from fitting of the PLK relations and assuming a mean metallicity of -1.83 dex. The following values calculated as the mean from the 29 individual true distance moduli were obtained: 19.60 ± 0.05 (Sollima et al., K band), 19.69 ± 0.05 (Bono et al, K band), 19.66 ± 0.04 (Catelan et al., K band), and 19.68 ± 0.06 (Catelan et al., J band). As can be seen these moduli are fully consistent with the values listed in the Table 4.

6. Summary and Conclusions

We have determined the distance to the Local Group Sculptor dwarf galaxy from single-phase near-infrared observations in J and K of 78 RR Lyrae stars. Different calibrations of the near-infrared PLZ relation for RR Lyrae stars yield closely consistent distance results which also agree with the distance modulus derived from optical V-band data.

While our data are very well suited for a precise distance determination to this galaxy, it will be necessary to secure additional data to study in detail the slope of the PLZ relation in J and K, and to perform a high-precision empirical determination of the metallicity dependence of the relation.

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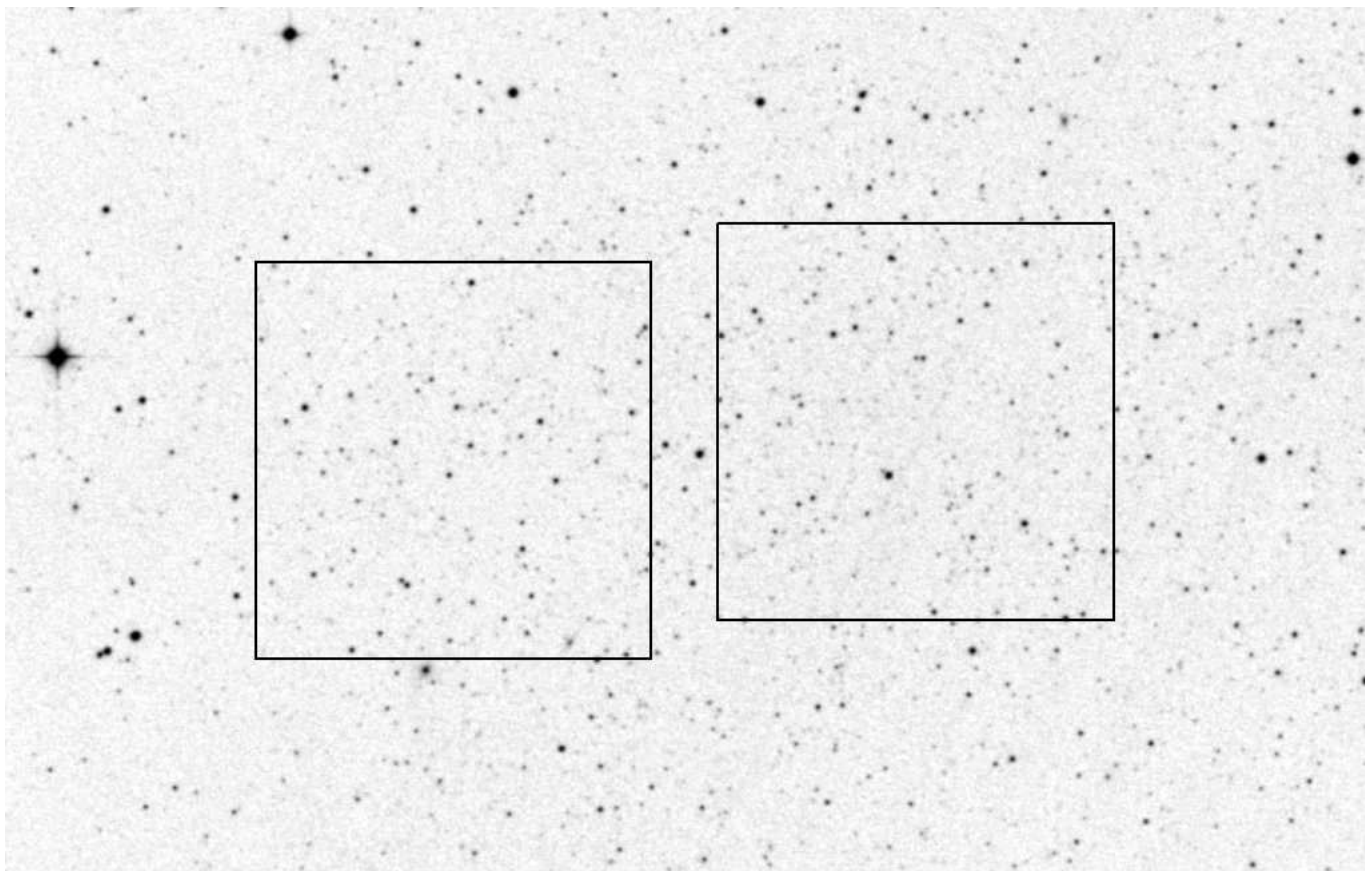


Fig. 1.— The location of our two observed 5 x 5 arcmin NTT/SOFI fields in Sculptor on the DSS blue plate. North is up and east to the left.

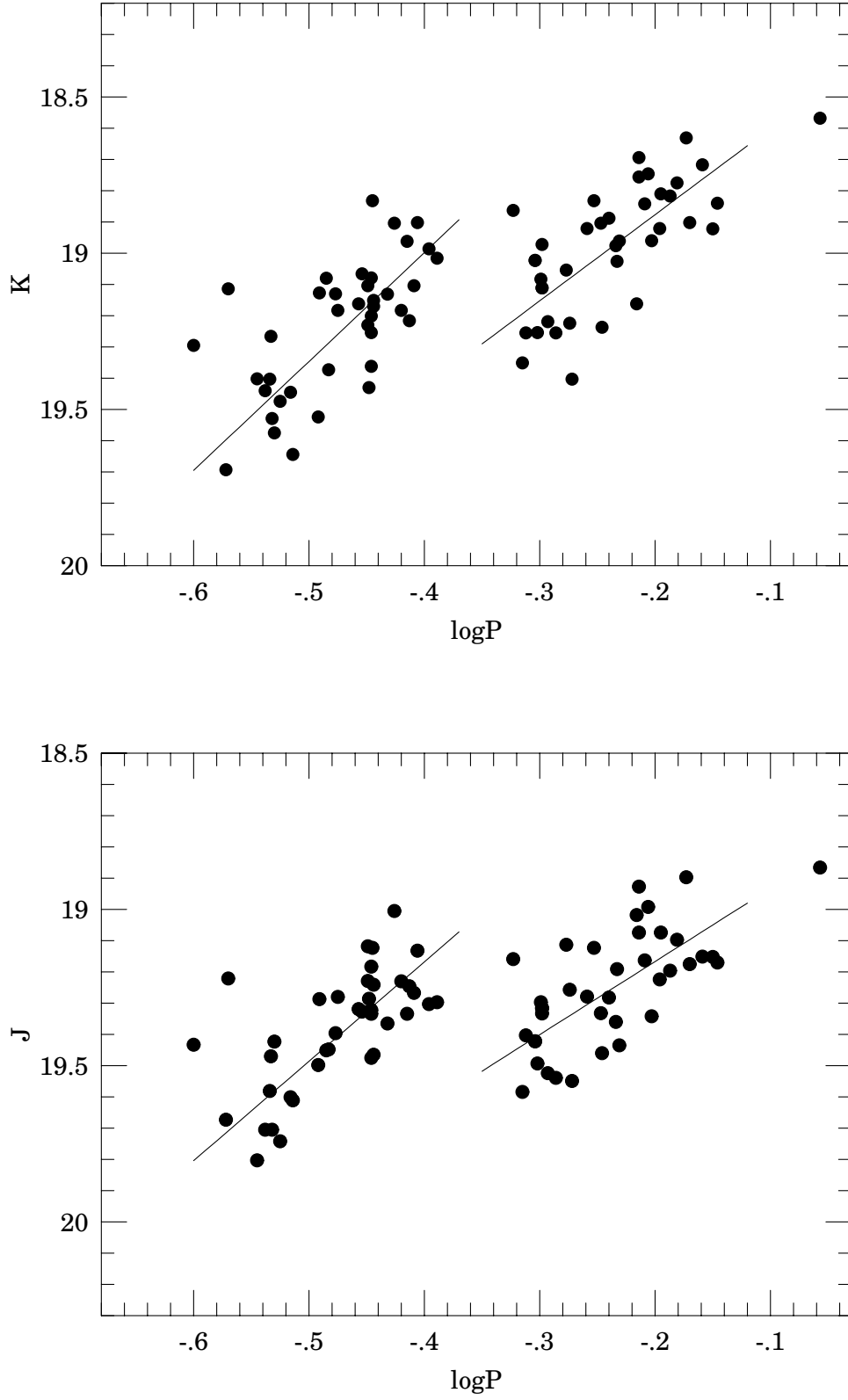


Fig. 2.— The near-infrared K and J band period-luminosity relations defined by the 78 RR Lyrae stars observed in Sculptor. Period is in days. Two sequences formed by the fundamental and first overtone pulsators are clearly seen in each panel. The free-fit lines for RRAb and RRC stars are indicated.

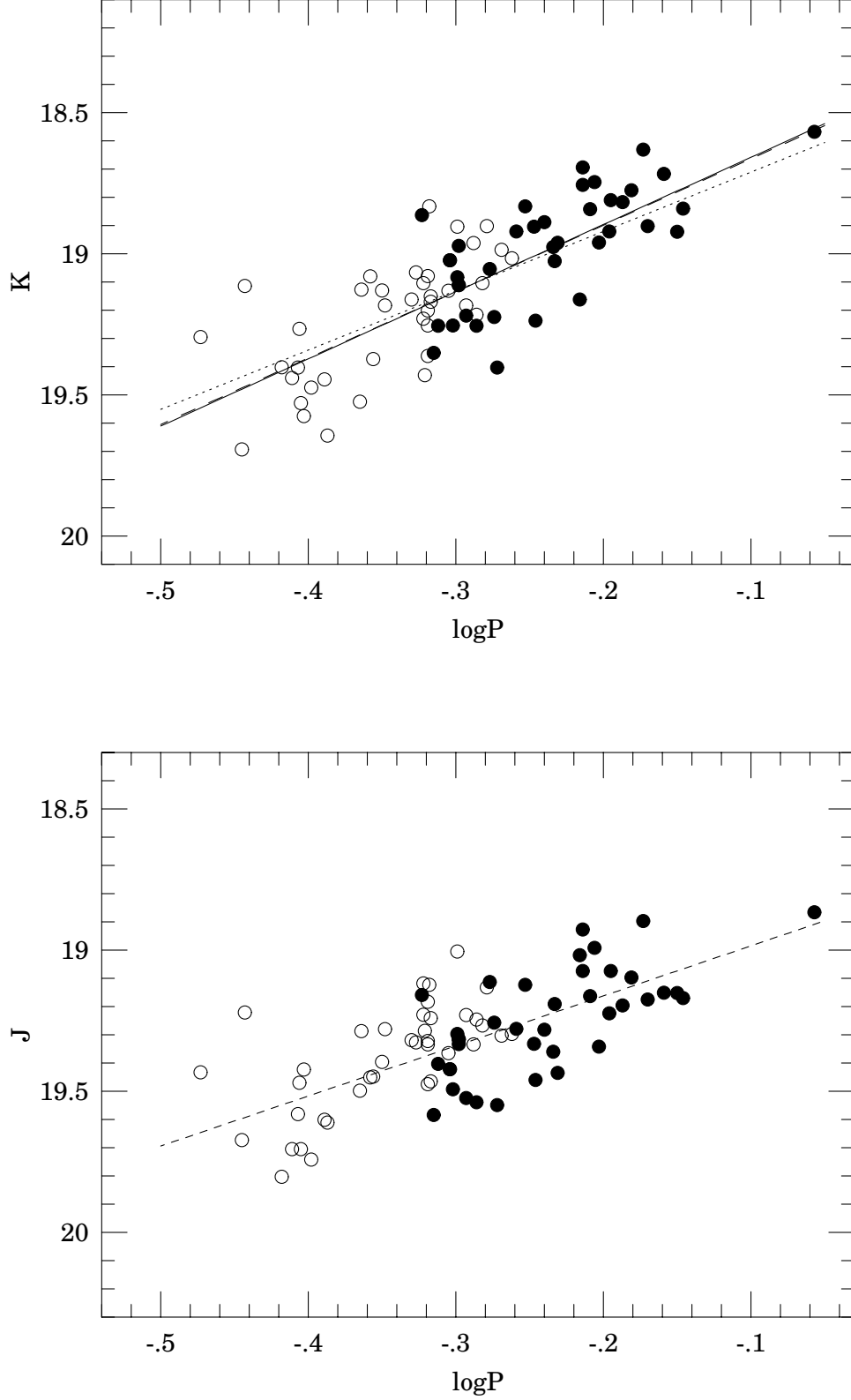


Fig. 3.— The near-infrared PL relations in K and J defined by our RR Lyrae sample in Sculptor, plotted along with the best-fitting lines. The filled and open circles stand for RRAb and RRC stars, respectively. The periods of the RRC stars have been adjusted by adding 0.127 in $\log P$. The slopes of the fits were adopted from the recent theoretical and empirical calibrations (equations 1-4; see text), and the zero points determined from our data. The solid, dotted and dashed lines correspond to the calibration of Sollima et al., Bono et al. and Catelan et al., respectively.

Table 1. Journal of the Individual J and K band Observations of RR Lyrae stars in Sculptor

ID	J HJD 2400000+	J mag	σ mag	K HJD 2400000+	K mag	σ mag
377	53371.08459	19.42	0.06	53371.04170	19.57	0.08
1823	53371.08459	19.74	0.08	53371.04170	19.47	0.08
1824	53371.08459	19.16	0.06	53371.04170	18.86	0.05
1830	53371.08459	19.54	0.07	53371.04170	19.25	0.07
1838	53371.08459	19.15	0.06	53371.04170	18.92	0.05
1873	53371.08459	19.58	0.08	53371.04170	19.40	0.07
1874	53371.08459	19.22	0.06	53371.04170	19.11	0.06
1875	53371.08459	19.40	0.07	53371.04170	19.13	0.07
1877	53371.08459	19.46	0.07	53371.04170	19.24	0.06
1943	53371.08459	19.28	0.08	53371.04170	18.92	0.07
1997	53371.08459	19.34	0.06	53371.04170	18.96	0.06
2004	53371.08459	19.43	0.07	53371.04170	18.96	0.05
2012	53371.08459	19.17	0.06	53371.04170	18.84	0.05
2021	53371.08459	18.99	0.05	53371.04170	18.75	0.05
2048	53371.08459	19.32	0.06	53371.04170	19.25	0.06
2058	53371.08459	19.32	0.06	53371.04170	19.11	0.06
2059	53371.08459	19.42	0.06	53371.04170	19.02	0.06
2410	53371.08459	19.26	0.06	53371.04170	19.22	0.07
2421	53371.08459	19.30	0.06	53371.04170	19.02	0.05
2422	53371.08459	19.58	0.08	53371.04170	19.35	0.07
2423	53371.08459	19.12	0.05	53371.04170	18.83	0.06
2424	53371.08459	19.32	0.06	53371.04170	19.16	0.07
2425	53371.08459	18.87	0.05	53371.04170	18.57	0.04
2450	53371.08459	19.16	0.06	53371.04170	18.84	0.05
2455	53371.08459	19.22	0.06	53371.04170	18.92	0.05
2458	53371.08459	19.33	0.07	53371.04170	19.36	0.09
2467	53371.08459	19.48	0.08	53371.04170	19.20	0.07
2470	53371.08459	19.15	0.06	53371.04170	18.72	0.04
2471	53371.08459	19.20	0.06	53371.04170	18.82	0.05
2482	53371.08459	19.67	0.07	53371.04170	19.69	0.10
2502	53371.08459	19.45	0.06	53371.04170	19.08	0.06

Table 1. Journal of the Individual J and K band Observations of RR Lyrae stars in Sculptor - Continuation

ID	J HJD 2400000+	J mag	σ mag	K HJD 2400000+	K mag	σ mag
2552	53371.08459	19.55	0.09	53371.04170	19.40	0.09
2555	53371.08459	19.30	0.07	53371.04170	19.08	0.06
2558	53371.08459	19.32	0.06	53371.04170	19.11	0.06
2559	53371.08459	19.42	0.06	53371.04170	19.02	0.06
2562	53371.08459	19.25	0.06	53371.04170	19.22	0.06
2566	53371.08459	19.36	0.06	53371.04170	18.98	0.05
2575	53371.08459	18.93	0.04	53371.04170	18.69	0.05
2606	53371.08459	19.19	0.07	53371.04170	19.03	0.06
2627	53371.08459	19.28	0.06	53371.04170	18.89	0.05
2639	53371.08459	19.70	0.09	53371.04170	19.44	0.08
3916	53371.08459	19.60	0.08	53371.04170	19.45	0.09
3931	53371.08459	19.46	0.07	53371.04170	19.17	0.07
4233	53371.08459	19.12	0.05	53371.04170	18.83	0.06
4353	53371.08459	19.24	0.07	53371.04170	19.15	0.07
4385	53371.08459	19.40	0.07	53371.04170	19.25	0.08
3761	53371.13750	19.33	0.07	53371.09050	18.96	0.06
3763	53371.13750	19.50	0.09	53371.09050	19.52	0.09
3777	53371.13750	19.07	0.06	53371.09050	18.81	0.05
3801	53371.13750	19.36	0.07	53371.09050	19.13	0.07
3832	53371.13750	19.29	0.09	53371.09050	19.43	0.11
3834	53371.13750	19.00	0.06	53371.09050	18.90	0.06
3862	53371.13750	19.70	0.10	53371.09050	19.53	0.09
3888	53371.13750	19.02	0.05	53371.09050	19.16	0.07
3938	53371.13750	19.23	0.06	53371.09050	19.18	0.07
4235	53371.13750	19.23	0.06	53371.09050	19.10	0.06
4263	53371.13750	19.80	0.11	53371.09050	19.40	0.07
4277	53371.13750	19.61	0.22	53371.09050	19.64	0.20
5330	53371.13750	19.13	0.06	53371.09050	18.90	0.06
5354	53371.13750	19.18	0.07	53371.09050	18.90	0.06
5359	53371.13750	18.90	0.05	53371.09050	18.63	0.05
5375	53371.13750	19.30	0.08	53371.09050	18.99	0.06
5376	53371.13750	19.27	0.07	53371.09050	19.10	0.06
5384	53371.13750	19.28	0.07	53371.09050	19.18	0.08
5390	53371.13750	19.10	0.06	53371.09050	18.77	0.05

Table 1. Journal of the Individual J and K band Observations of RR Lyrae stars in Sculptor - Concluded

ID	J HJD 2400000+	J mag	σ mag	K HJD 2400000+	K mag	σ mag
5393	53371.13750	19.29	0.07	53371.09050	19.13	0.07
5400	53371.13750	19.45	0.09	53371.09050	19.37	0.08
5401	53371.13750	19.33	0.08	53371.09050	18.97	0.06
5492	53371.13750	19.11	0.07	53371.09050	19.05	0.07
5710	53371.13750	19.12	0.07	53371.09050	19.23	0.08
5714	53371.13750	19.47	0.08	53371.09050	19.27	0.08
5721	53371.13750	19.18	0.07	53371.09050	19.08	0.07
5723	53371.13750	19.33	0.07	53371.09050	18.90	0.06
5724	53371.13750	19.49	0.09	53371.09050	19.25	0.07
5728	53371.13750	19.43	0.08	53371.09050	19.30	0.08
5730	53371.13750	19.33	0.08	53371.09050	19.07	0.06
5773	53371.13750	19.52	0.09	53371.09050	19.22	0.08
5778	53371.13750	19.07	0.09	53371.09050	18.76	0.08

Table 2. The Slopes of the K and J band PL relations calculated for Sculptor RRa, RRc type stars and the combined sample.

sample	K	σ	J	σ
RRc	-2.60	0.48	-2.32	0.43
RRab	-2.42	0.39	-2.11	0.37
all	-2.44	0.22	-1.72	0.21

Table 3. Observed Near-Infrared Distance Moduli for Sculptor obtained from different theoretical and empirical calibrations.

Calibration	$(M - m)_K$ Sollima et al.	$(M - m)_K$ Bono et al.	$(M - m)_K$ Catelan et al.	$(M - m)_J$ Catelan et al.
RRab	19.641 ± 0.023	19.712 ± 0.023	19.669 ± 0.023	19.684 ± 0.022
RRab + RRc	19.643 ± 0.017	19.727 ± 0.017	19.686 ± 0.017	19.686 ± 0.017

Table 4. Reddening-corrected V, J and K Band Distance Moduli for Sculptor obtained from RR Lyrae stars and using different theoretical and empirical calibrations. The reddening law of Schlegel et al (1998) was assumed, and the foreground reddening $E(B-V) = 0.018$ toward the Sculptor galaxy was calculated using reddening maps from this same paper.

Filter	K	K	K	J	V
data	this paper	this paper	this paper	this paper	Kaluzny et al. (1995)
Calibration	Sollima et al.	Bono et al.	Catelan et al.	Catelan et al.	Sandage 1993
$(m - M)_0$	19.64	19.72	19.68	19.66	19.67
statistical error	0.02	0.02	0.02	0.02	0.08
systematic error	0.15	0.13	0.12	0.12	0.18